FINAL TECHNICAL REPORT
JPL Task Plan 70-6362
JPL Task Order 15407

GREAT LAKES ICE MAPPING WITH SATELLITE SCATTEROMETER DATA

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27 May 2003

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ABSTRACT

We develop algorithms for Great Lakes ice cover mapping with satellite scatterometer data acquired by NASA satellite Ku-band scatterometers. The wide-swath scatterometers provide a large spatial coverage with high temporal resolution data to map Great Lakes ice cover for applications to marine resource management, lake fisheries and ecosystem studies, and Great Lakes climatology. This project can provide important ice cover information derived from scatterometer data to the NOAA Great Lakes CoastWatch node for public distribution via the Internet through the Great Lakes CoastWatch web site. The approach is to use in-situ and ground truth measurements from our 1997 Great LAkes Winter EXperiments (GLAWEX 1997) and from the Great Lakes Marine Weather Network in conjunction with concurrent satellite SAR data from ERS and RADARSAT and scatterometer data to determine scatterometer backscatter signatures of different lake ice types. The backscatter signatures are used to develop the ice-mapping algorithm using NSCAT and SeaWinds data. The verification of ice mapping results is carried out with in-situ observations from US Coast Guard (USCG) icebreaker vessels. In addition, we installed and operated a web camera on Granite Island to monitor ice cover over an area in Lake Superior to verify time-series scatterometer results. Potential users of the ice mapping results include the National Oceanic and Atmospheric Administration (NOAA) CoastWatch, National Weather Service (NWS), US National Ice Center (NIC), US Coast Guard (USCG), Canadian Ice Service (CIS), Canadian Coast Guard (CCG), and the Great Lakes Research Consortium.

1. OBJECTIVE

The objective is to develop algorithms for Great Lakes ice cover mapping using satellite scatterometer data with a large spatial coverage and a high temporal resolution for applications to marine resource management, lake fisheries and ecosystem studies, Great Lakes climatology, and ice cover information distribution (winter navigation). Scatterometer data have been acquired over the Great Lakes by NSCAT (NASA Scatterometer) on ADEOS (ADvanced Earth Observing Satellite) in 1996 and 1997, and by the SeaWinds Scatterometer (denoted as QSCAT hereon) currently operational on the QuikSCAT satellite (launched in June 1999). The follow-on SeaWinds scatterometer launched on the Japanese Midori-II Satellite in December 2002, together with the present scatterometer data sets, can provide long-term decadal data for Great Lakes ice mapping. This project enables the derivation of ice cover information from NASA scatterometer data over the Great Lakes.

2. BACKGROUND

2.1. Science and Applications of Great Lakes Ice Cover Mapping

Ice cover information is necessary for resource management. For fisheries, ice cover area is needed to forecast the abundance of lake fish. A whitefish recruitment forecast model uses, as an important input parameter, the number of days that ice cover exceeded 40% during egg incubation for northern Green Bay and North Shore areas of Lake Michigan [*Brown et al., J. Great Lakes Res., 19(2), 418-428*, 1993].

To the hydropower industry, ice is potentially harmful to the installations on the Niagara River [*Assel et al., Great Lakes Ice Atlas, Ann Arbor, MI*, 1983]. Ice information is valuable to the shipping industry and to all involved in winter navigation. Extending the winter navigation season can save millions of dollars in coal and ore shipping [*Cooper et al., NASA Tech. Mem. TM X-71808*, 1975].

Winter ecology is strongly affected by the ice cover reduction, which influences the stable environment necessary to various levels of the food chain [*Vanderploeg et al., Hydrobiologica,* 243-244, 175-183, 1992]. The change modifies and degrades the Great Lakes wetland and deep water habitats of many species; large concentrations of mallards, American black ducks, and mergansers are found on ice-free areas during winter [*Prince et al., J. Great Lakes Res., 18(4), 673-699*, 1992].

Global climate change could have a significant impact on the Great Lakes. Several General Circulation Models (GCM) predict a reduction of ice cover duration by 5 to 13 weeks under the CO_2 doubling scenario [*Assel, Climate Change, 18(4), 377-395*, 1991]. Freezeup and breakup dates represent integrated climatic conditions during the winter-spring period when most warming is forecast to occur; this timing provides an early indication of climatic warming [*Assel and Robertson, Limno. and Ocean., 40(1), 165-176,* 1995].

Ice cover information is also important to hazard prediction. Ice jams not only impede navigation but can also cause dangerous flooding. Ice imported from southern Lake Huron creates large ice jams on the St. Clair River. Ice passage can be forecast based on the mean surface ice cover fraction, correlated to the presence or absence of the ice arch corresponding to 9.5% and 27.3% ice concentration, respectively [*Daly, J. Great Lakes Res., 18(1), 61-69*, 1992].

Lake ice coverage and freezeup and breakup dates can be used as an index of winter severity. Another ice-related problem is the damage of shore structures [*Assel et al., Great Lakes Ice Atlas, Ann Arbor, MI*, 1983]. Ice rafting causes coastal sediment loss by drifting ice, which is important to coastal erosion processes [*Reimnitz et al., J. Coastal Res., 7(3), 653-664*, 1991]. The science studies and applications discussed above require information about ice cover over the Great Lakes.

2.2. Background of Great Lakes Ice Cover Mapping Project

We have carried out a NOAA/NESDIS/COP project entitled "Satellite SAR Remote Sensing of the Great Lakes Ice Cover" for the period from August 1996 to November 1998. The SAR project is to develop algorithms to map Great Lakes ice areal coverage and ice types from RADARSAT and ERS SAR data. We conducted field experiments during February and March 1997 (Great LAkes Winter EXperiment in 1997 – GLAWEX 1997) on board two different US Coast Guard icebreaker vessels (the Mackinaw and the Biscayne Bay) with concurrent RADARSAT SAR, ERS SAR, and NSCAT Scatterometer overflights. The ice mapping algorithm and results are presented in our 1998 NOAA report (*NOAA assigned project no. 56,* 1998).

The GLAWEX 1997 field experiments provide radar backscatter signature measurements and in-situ surface truth, which are successfully used to develop algorithms for ice mapping using satellite ERS and RADARSAT SAR data. Ice mapping results from satellite SAR images can then be used to derive NSCAT backscatter signatures for different ice types and to train concurrent NSCAT images for ice classification. The surface field observations, which were obtained from the 1997 experiments, are useful for result verification.

Polarimetric radar backscatter measurements from the USCG ship acquired during GLAWEX 1997 reveal that horizontally polarized backscatter (HH) is larger than vertically polarized backscatter (VV) for the typical snow-covered snow ice on lake ice in the Great Lakes while VV is larger than HH over open water areas regardless of wind speeds. In dB scale, HH/VV is simply positive for ice, while HH/VV is negative for open water. The significant implication of these results is that ice and open water can be detected using dual polarization data without the ambiguity encountered in single polarization data due to variations in wind speed over water. For QSCAT, the incidence angle for each beam is kept constant, and thus further facilitates the ice-mapping algorithm. However, the different geometry of QSCAT necessitates new algorithms.

2.3. Potential Use of Scatterometer Data for Great Lakes Ice Mapping

To illustrate the potential application for Great Lakes ice and open water mapping, we use NSCAT HH/VV data to map ice cover over the Great Lakes in 1997. The NSCAT ice-cover image is obtained with coarse-resolution NSCAT data over a limit portion the swath without any data interpolation, data subsampling, land-masking improvement, nor geolocation improvement. Nevertheless, the NSCAT results are in good agreement with NIC ice charts laboriously derived from ice reconnaissance, ship, shore, visible/infrared, and radar data. NSCAT ice mapping results in February-March 1997 show that western Lake Superior was frozen up while the eastern part was still open water, and that Lake Erie (at lower latitude) was mostly frozen solid while the upper lakes were only partially ice covered. This ice coverage behavior is related to lake bathymetry. Such ice cover trend profoundly impacts the heat fluxes (both sensible and latent) between lake water and the atmosphere, and thus influences the local and regional climate patterns. We have presented these NSCAT ice-mapping results elsewhere [*Nghiem and Leshkevich, Development of a Satellite Scatterometry Approach for Great Lakes Ice Cover Mapping, Invited Paper*, *International Association of Great Lakes Research*, Greenbay, Wisconsin, 2001]. While, these results are promising, the NSCAT ice-mapping algorithm cannot be applied directly to QSCAT data because the configuration and orbital geometry of these two satellite scatterometers are quite different. We have developed a new algorithm using QSCAT for Great Lakes ice mapping, which will also be applicable to the new Midori-II/SeaWinds scatterometer data set, and present the results in this report.

3. APPROACH

3.1. Methodology

Our approach includes the following steps: Use of GLAWEX 1997 field experiment data with concurrent ERS SAR, RADARSAT SAR, and NSCAT data to obtain Ku-band backscatter signatures over various ice types and open water; analyzing time-series backscatter signatures; and developing scatterometer mapping algorithms based on Ku-band backscatter signatures of Great Lakes ice and water. Algorithms include: Great Lakes land masking; scatterometer data collocation and geocoding; subsampling data to produce gridded backscatter data; training scatterometer data with validated SAR ice mapping results; and determining Ku-band parameter set to classify and map the ice cover automatically. We apply algorithms to QSCAT data to derive ice areal coverage and/or ice classes. We plan to verify ice-mapping results with in-situ observations provided by US Coast Guard (USCG) icebreaker vessels operating over the Great Lakes under the jurisdiction of the Ninth Coast Guard District. Furthermore, we use our web on the Granite Island to record time-series lake ice conditions to verify scatterometer results.

3.2. Scatterometer Data

The entire NSCAT data set over the 9-month period of its radar operation (approximately 80 Gigabytes) is readily available at JPL. NSCAT has 8 antenna beams collecting backscatter data at vertical polarization (6 beams) and horizontal polarization (2 beams) on both sides of the satellite ground track. QSCAT has an 1800-km swath for backscatter at vertical polarization and a 1400-km swath for the horizontal polarization. Global data are collected providing 2.5 Gigabytes of data per day. QSCAT can cover most of the Great Lakes twice daily with some missing wedges at low latitudes in the Great Lakes region. Midori-II/SeaWinds data, with a configuration and geometry similar to those of QSCAT, will be released after the completion of the satellite calibration and validation.

3.3. Project Resources

We list the resources at NASA JPL and NOAA GLERL to successfully complete the proposed work: Great Lakes field experiment data (ground truth data), ancillary data from NOAA Great Lakes CoastWatch, concurrent RADARSAT data over the Great Lakes, concurrent ERS data over the Great Lakes, ice mapping data/results from ERS and RADARSAT, ENVISAT data set, NSCAT data set, and QSCAT global backscatter data. Our equipment includes: JPL Unix Ultra 60, dual 360-MHz coprocessors, 1.7 Gigabyte RAM, 0.65 Terabyte hard disks, internal CD, floppy drive, tape drive, JPL Unix Ultra 1, Unix Ultra1, Solaris 2.5.1, 143 MHz, 448-MByte RAM, 2.1-Gbyte hard disk, 8.4-Gbyte multipack, 14-Gbyte unipack, SUN Unix 4/370 computer, Micro VAX computers, Personal Computer, laser and color printers; GLERL: Several SUN and SGI computers with peripherals, software to ingest/process/analyze QSCAT, NSCAT, ERS, RADARSAT, and ENVISAT data, Interactive Dynamic Language (IDL), ENVI image processing software, Fortran and C compilers, several plotting/image display software.

4. RESULTS

Unusually mild weather conditions occurred over the Great Lakes during the past several winters. In 1998-2002, there was almost no significant ice cover over the Great Lakes except shore ice, ice in protected bays, or ice over some limited parts of the lakes for short periods of time. During the last winter (January-March 2003), the Great Lakes region suffered anomalous and prolonged Arctic cold conditions. Consequently, three of the Great Lakes - Lake Superior, Lake Huron, and Lake Erie - have frozen over for the first time in nearly a decade [*CNN/Reuters*, *Three Great Lakes still frozen*, March 2003]. The St. Lawrence Seaway officials decided to postpone its opening for almost a week, from March 25 to March 31, and hoped that the ice conditions would be alleviated by then [*ABC/Reynolds*, *Frozen Assets Iced-Over Great Lakes Affect Commerce, Adds to Economic Woes*, March 2003]. The navigation delay may cause major disruptions down the supply chain and the timing is horrible for manufacturers dependent on materials like steel [*ABC/Reynolds*, 2003]. In the Duluth Harbor, ice was more than 2 feet thick in spots on the Duluth side, and was even thicker across the way in Superior, and year 2003 could have a very difficult opening as indicated by the Executive Director of the Duluth Seaway Port Authority [*NBC/Meryhew*, *Lake Superior: Pretty as a picture or 'pain in the ice'?* March 2003]. This year extensive ice cover conditions over the Great Lakes provided us the first opportunity to apply our satellite scatterometer ice mapping algorithm and obtain large-scale ice mapping results from QSCAT data.

4.1. Time-Series QSCAT Signatures at Stationary Locations over the Great Lakes

Ku-band backscatter signatures of Great Lakes ice are evaluated using the approach described in section 3.1. In addition, we retrieved time-series QSCAT data at fixed locations over the Great Lakes to examine the backscatter signature behavior during ice cover and ice free periods to help in the development of the ice-mapping algorithm. We call these locations "stations", which are listed in Table 1. The locations of the QSCAT Satellite Stations listed in Table 1 are plotted on a map of the Great Lakes in Figure 1. Around each station, a circle with a radius of 25 km approximately marks the area within which QSCAT data are obtained for the station.

At these station locations, QSCAT data are collected for a radius of 25 km around each station. Time-series backscatter data are obtained separately for ascending and descending orbits and for horizontal and vertical polarizations. Diurnal values are derived (ascending – descending, or morning – afternoon). Polarization differences (H-V in dB) and daily standard deviations are calculated. We show the time series results over the last winter-spring for West Superior, Huron, and Erie in Figures 2-4. The backscatter signatures indicate that the backscatter is high, the polarization difference is high, and the deviation is low during the ice cover period (February to April 2003, determined by concurrent RADARSAT SAR images).

NAME	LAKE AREA	N LATITUDE	W LONGITUDE
LAKE07	West Superior	$47^{o}30'$	$89^{o}30'$
LAKE08	North Superior	$48^{o}10'$	$87^{o}30'$
LAKE09	East Superior	$47^{o}30'$	$86^{o}30'$
LAKE10	North Michigan	$45^{o}00'$	$86^{o}30'$
LAKE11	South Michigan	$43^{o}00'$	$87^{o}06'$
LAKE12	Huron	$45^{o}00'$	$82^{o}20'$
LAKE13	Georgian Bay	$45^{o}15'$	$81^{o}00'$
LAKE14	Erie	$42^{o}15'$	$81^{o}12'$
LAKE15	Ontario	$43^{o}36'$	$78^{o}20'$

Table 1. Satellite Stations over the Great Lakes for QSCAT time-series records.

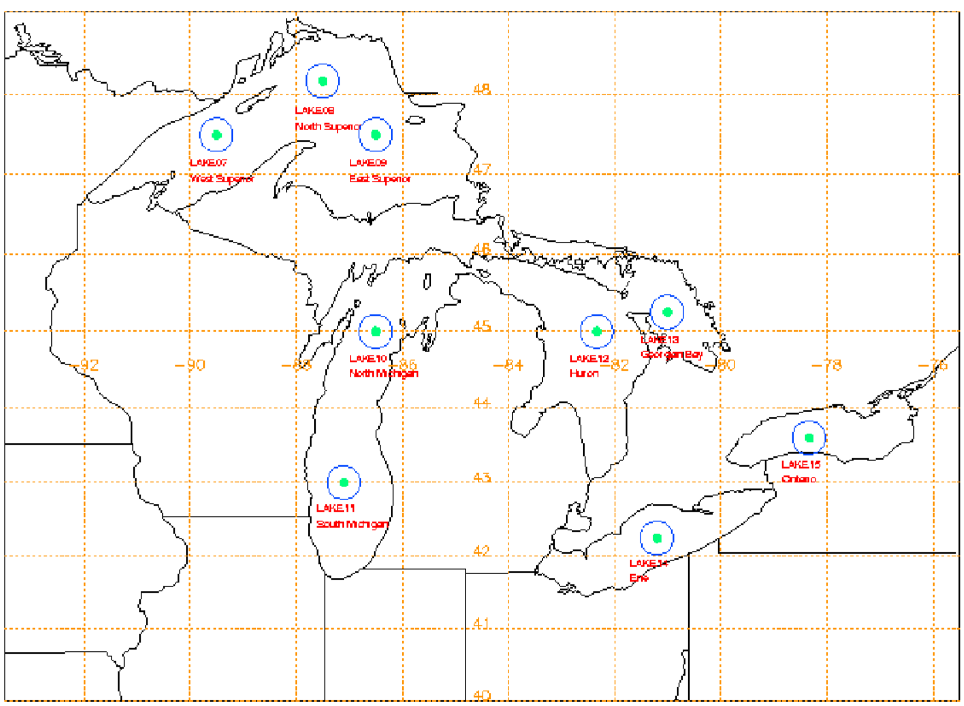


Figure 1. Locations of QSCAT Satellite Stations (green dot) and data areas (circle).

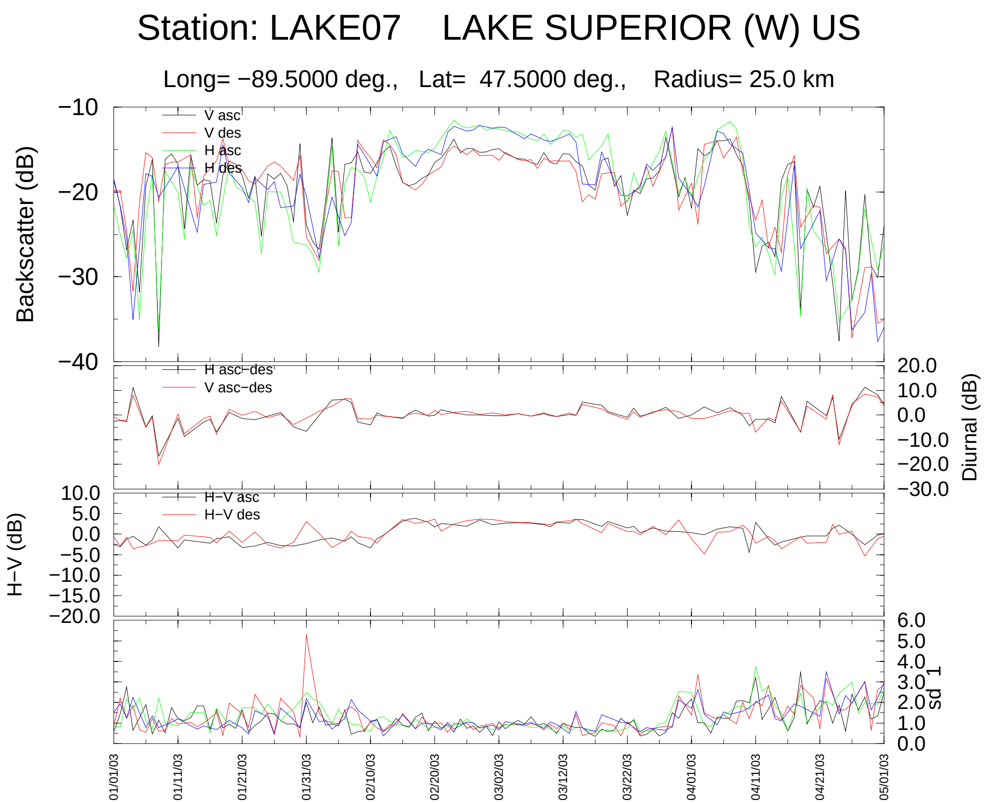


Figure 2. Time-series QSCAT signatures at Satellite Station West Superior.

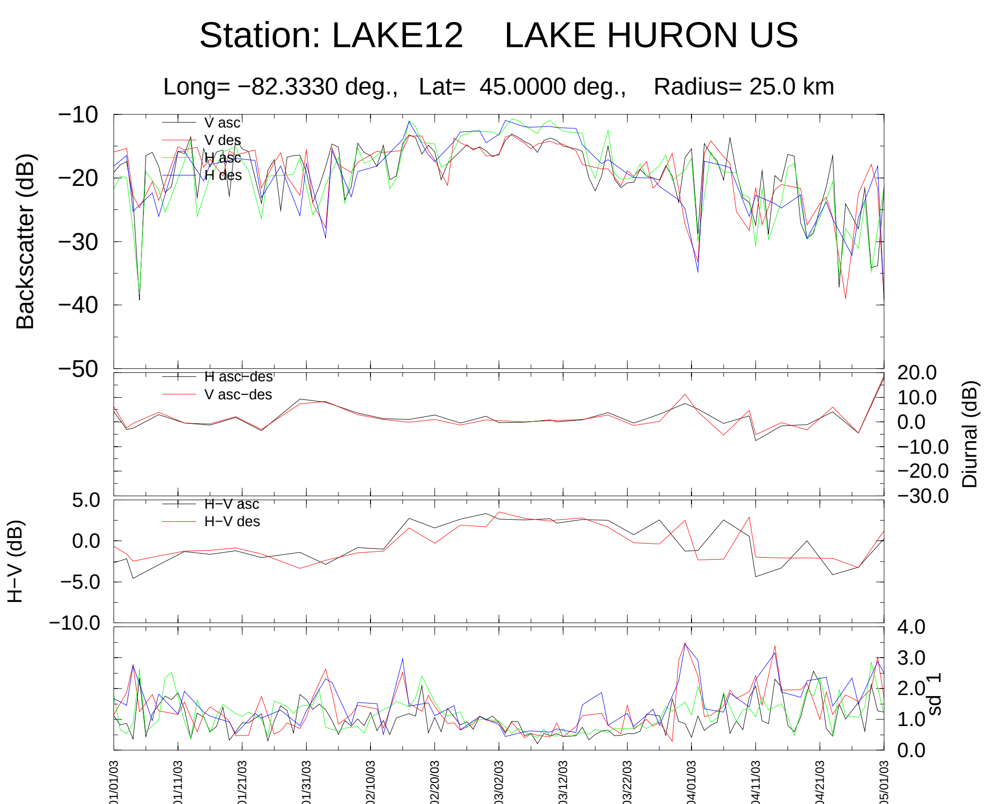


Figure 3. Time-series QSCAT signatures at Satellite Station Huron.

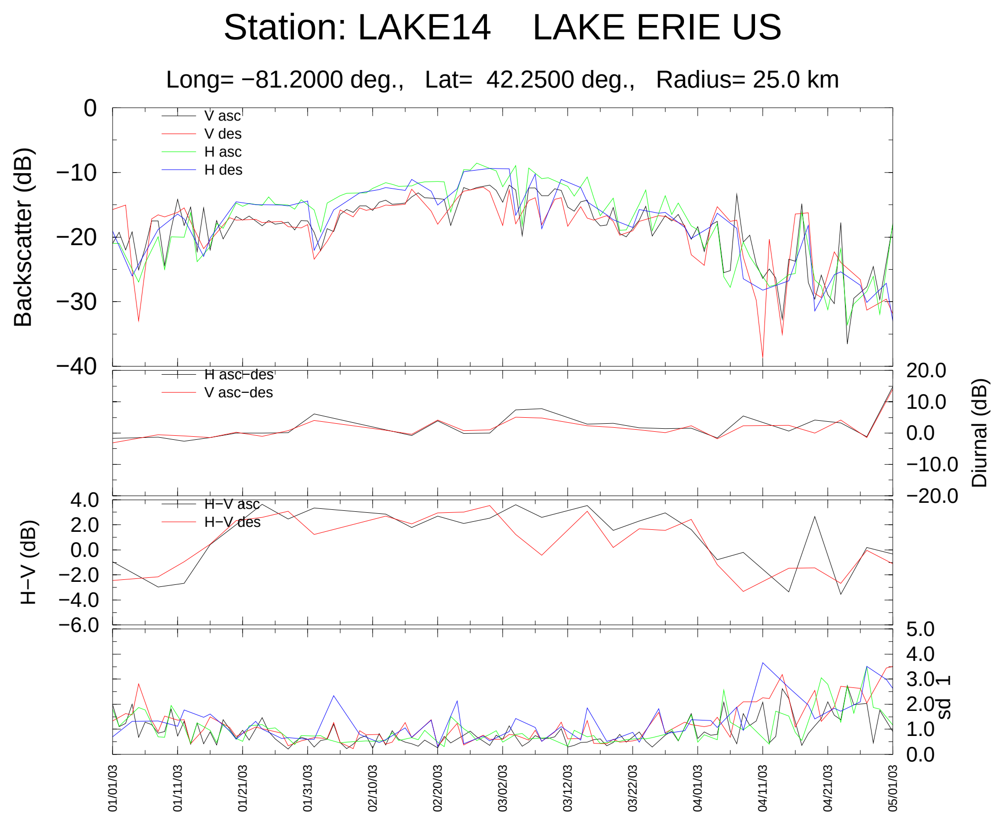


Figure 4. Time-series QSCAT signatures at Satellite Station Erie.

4.2. QSCAT Mapping of Great Lakes Ice Cover

The ice-mapping algorithm requires a strict collocation of QSCAT data in time and in space. For each pixel indexed by *ij*, we form a triplet of collocated and contemporaneous data consisting of forward-look backscatter with vertical polarization (VV_{for}), aft-look backscatter with vertical polarization (VV_{aft}), and forward-look backscatter with horizontal polarization (HH_{for}). Then, we calculate in the decibel (dB) domain the following set of parameters:

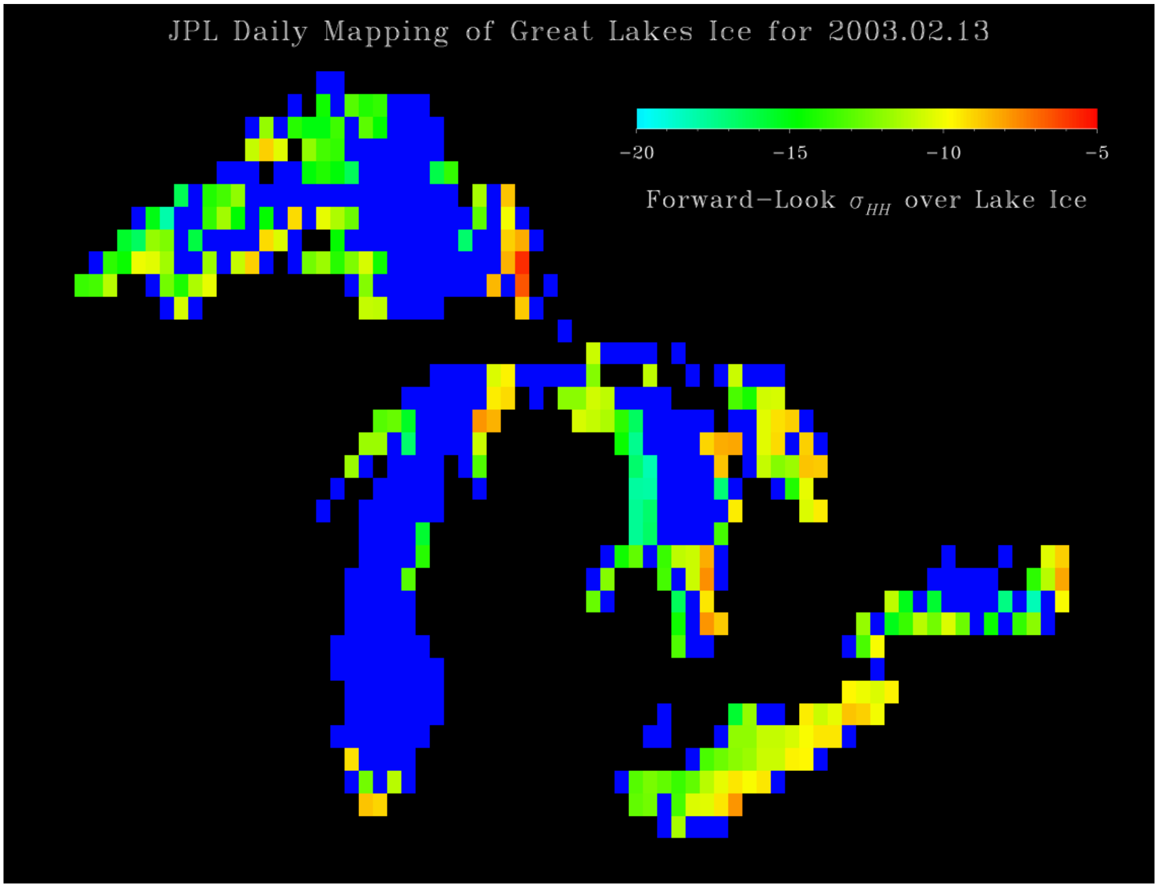
$$\Delta FA = |VV_{for} - VV_{aft}|$$
$$\Delta VH_{for} = VV_{for} – HH_{for}$$

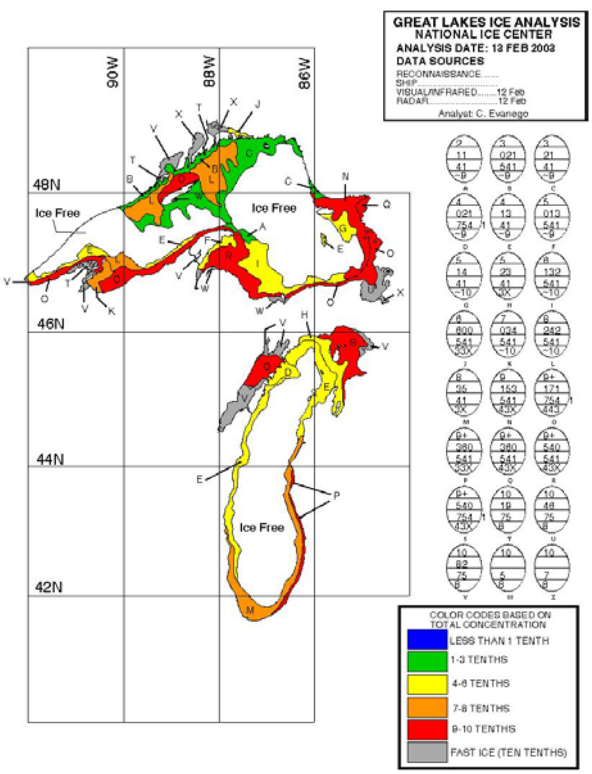
To classify ice cover and open water, we use the following algorithm:

(1) If ($HH_{for} > ice_{HH}$) and ($\Delta VH_{for} < ice_{VH}$) and ($\Delta FA < ice_{FA}$) for pixel *ij*, then we increase the ice count for pixel *ij* by 1; namely, Nice*ij*=Nice*ij*+1. Else, we increase the water count for pixel *ij* by 1; namely, Nwater*ij*=Nwater*ij*+1.

(2) If Nice*ij* > 0 from ascending and descending orbit passes, we classify pixel *ij* as ice. For Nwater*ij* > 0, we put pixel *ij* in the water class.

Based on backscatter signatures of ice and water discussed above, we select the following set of parameters for the classification: ice_{HH}=—20dB, ice_{VH}=0dB, and ice_{FA}=4dB.





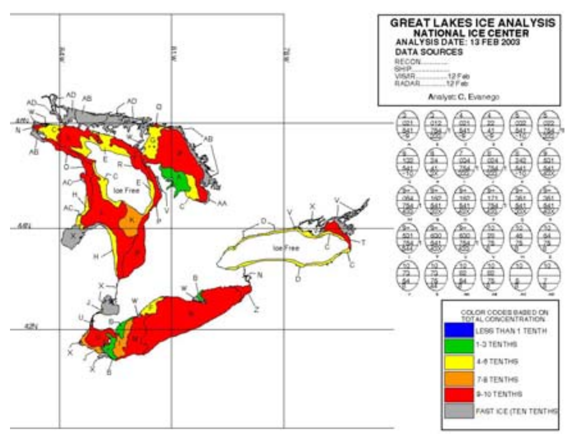
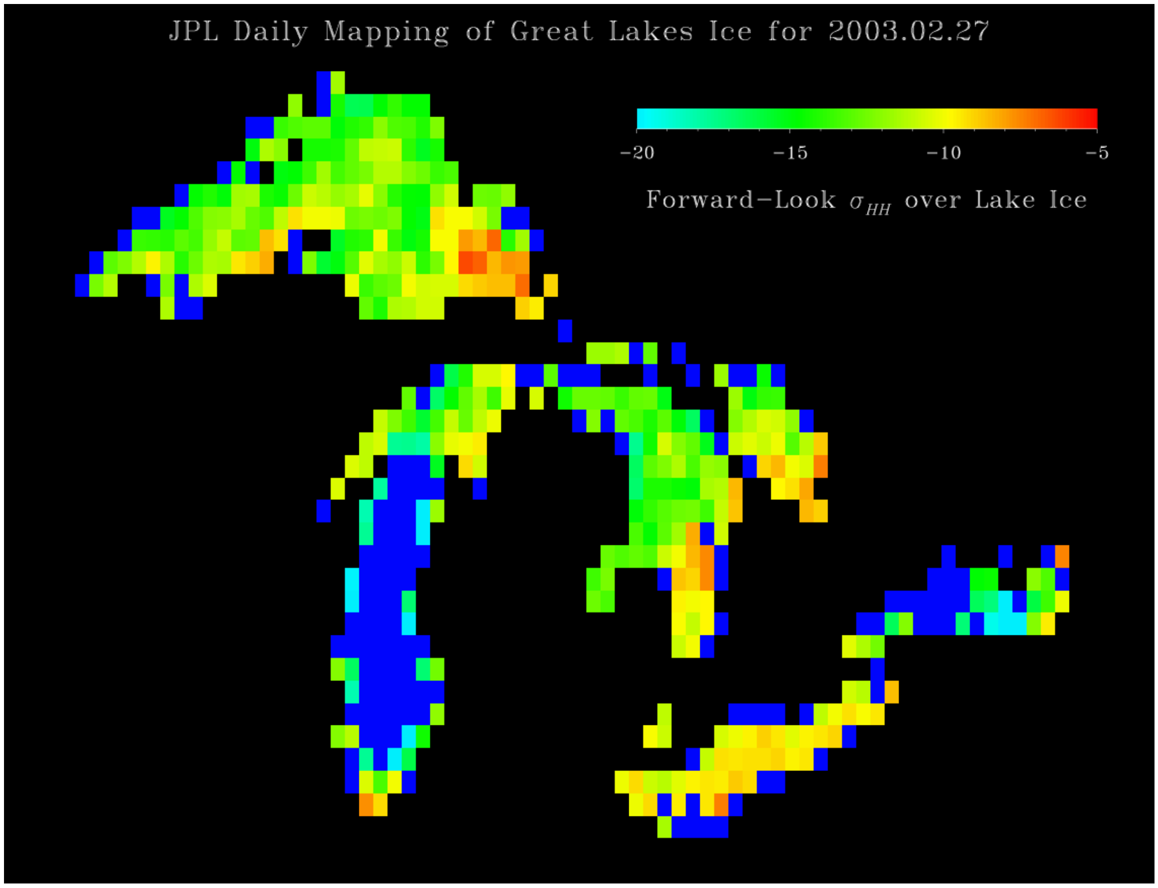
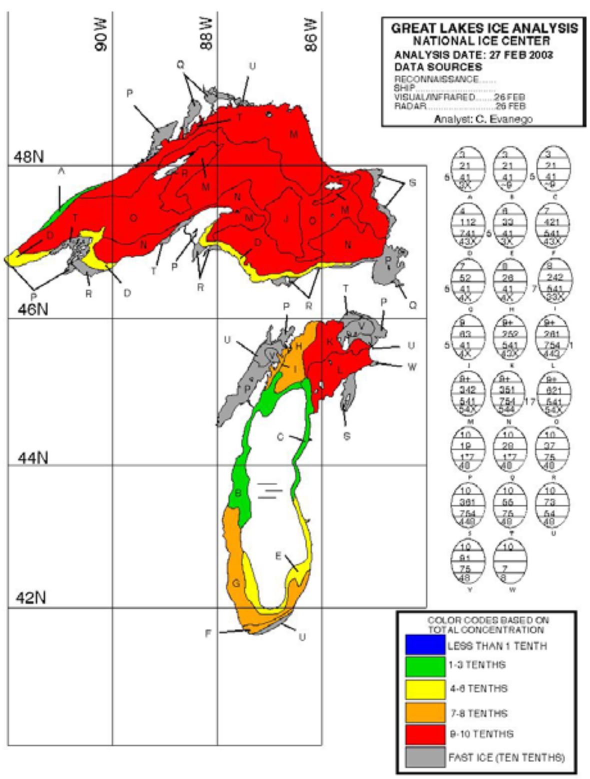


Figure 5. Ice cover over the Great Lakes observed by QSCAT (top) and NIC ice charts (bottom) for 2/13/2003.





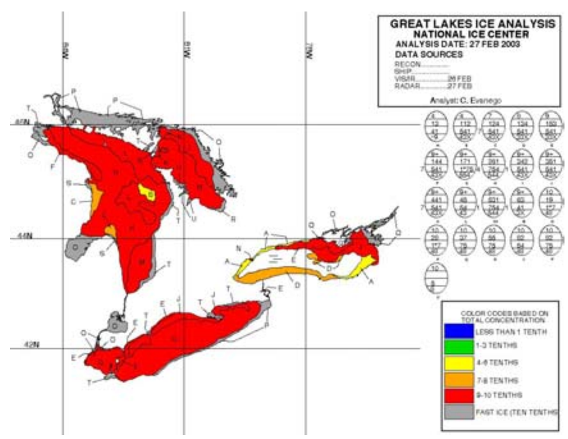
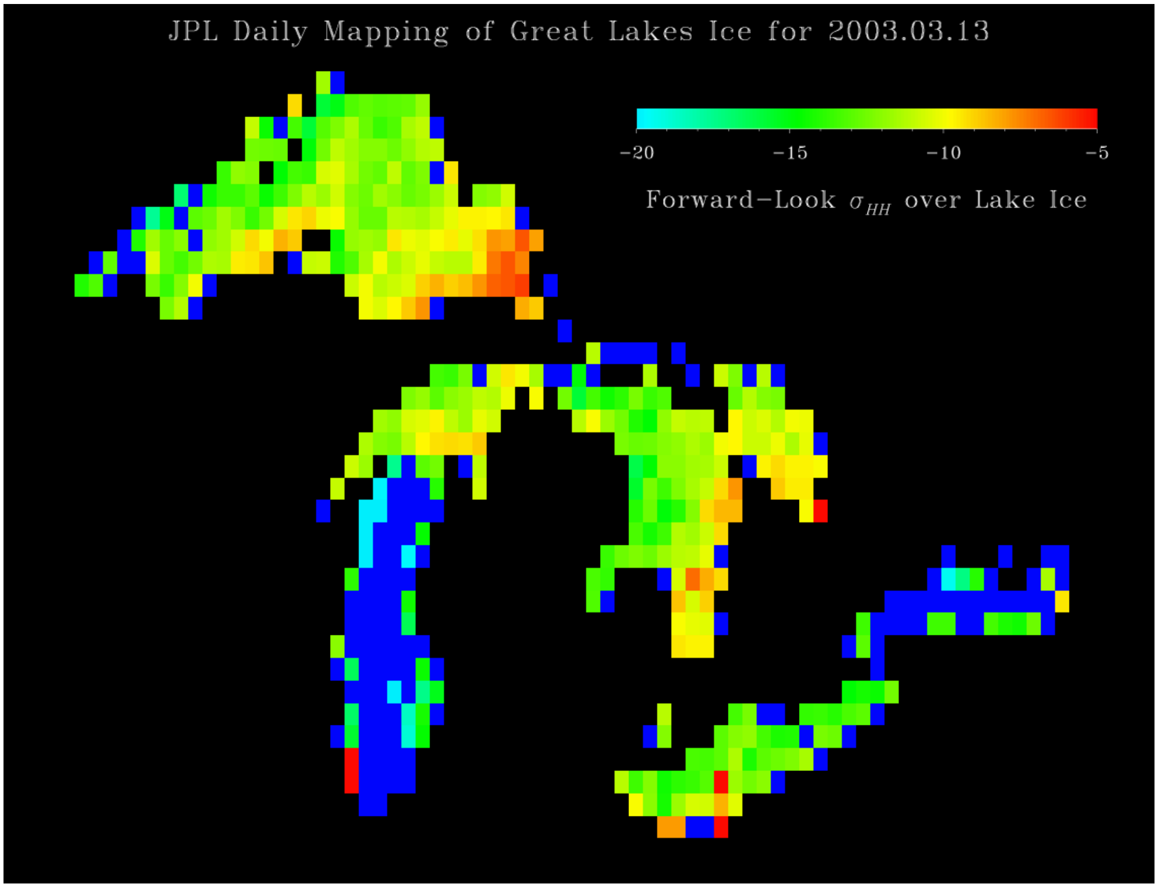
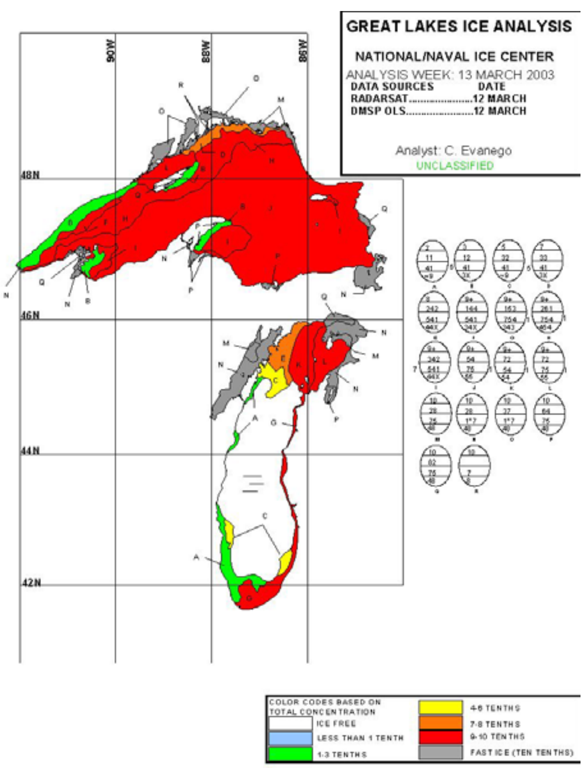


Figure 6. Ice cover over the Great Lakes observed by QSCAT (top) and NIC ice charts (bottom) for 2/27/2003.





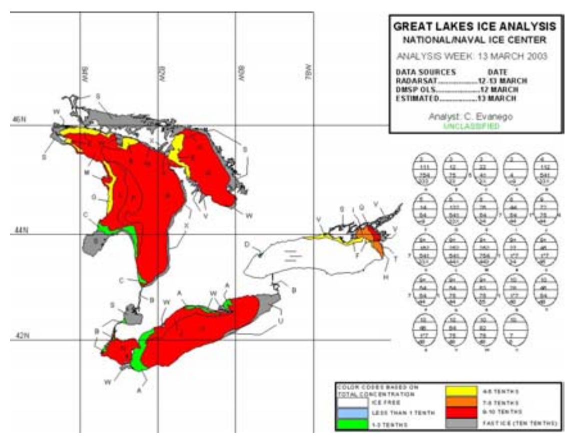
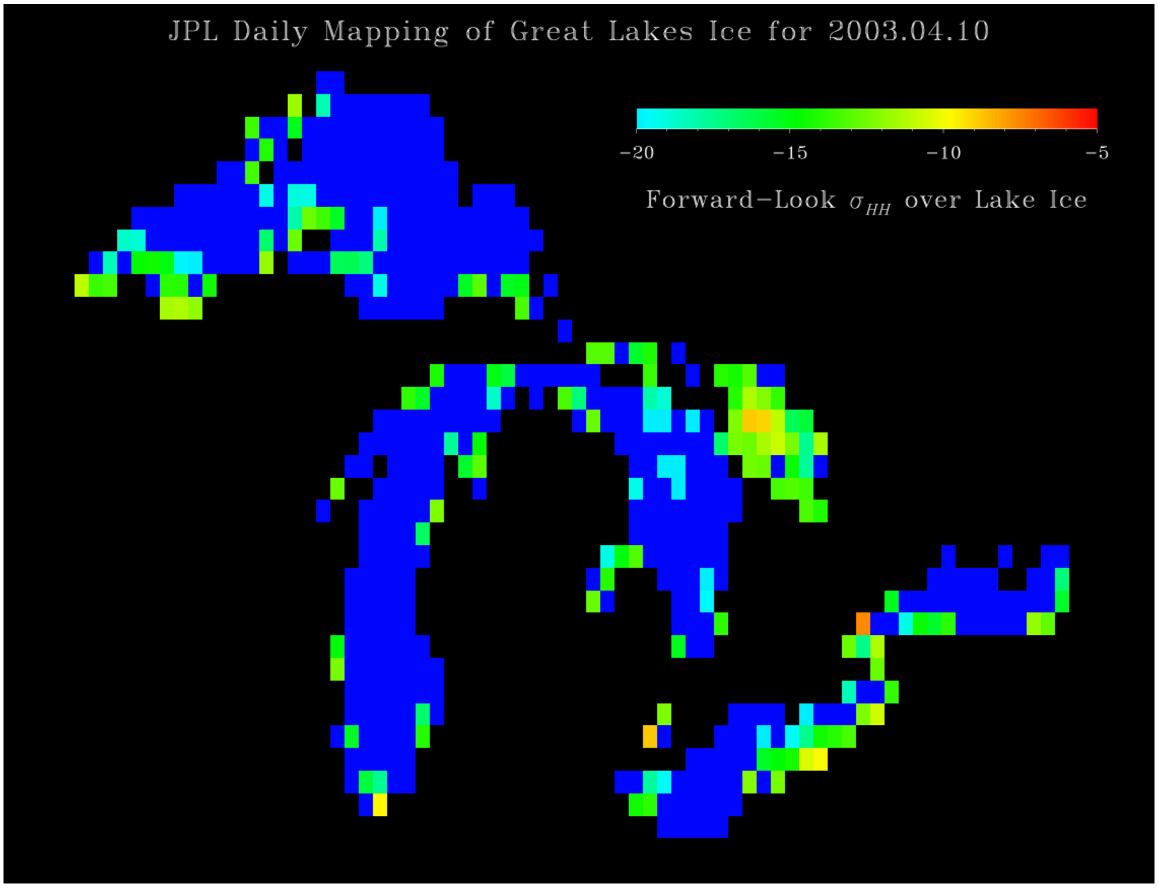
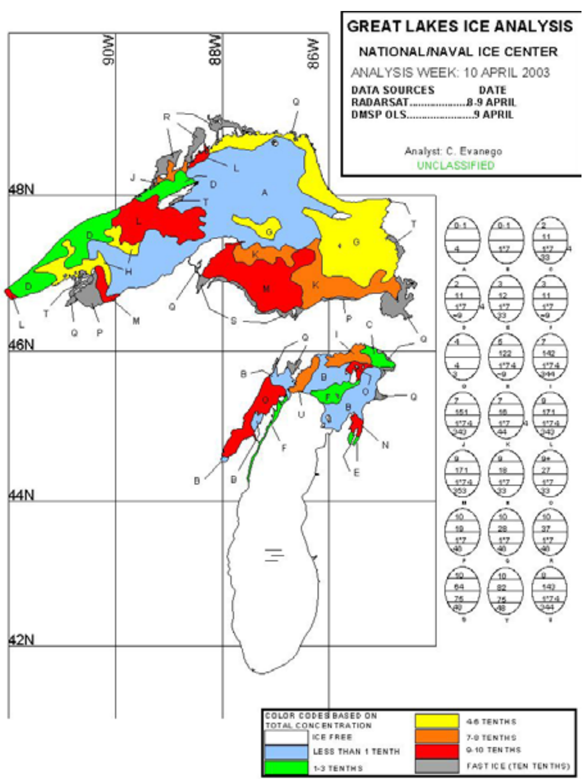


Figure 7. Ice cover over the Great Lakes observed by QSCAT (top) and NIC ice charts (bottom) for 3/13/2003.





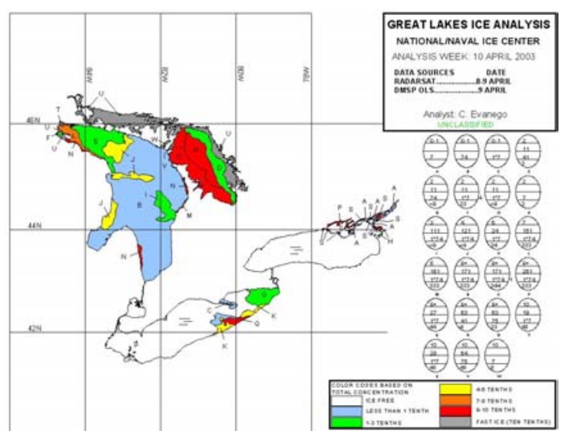
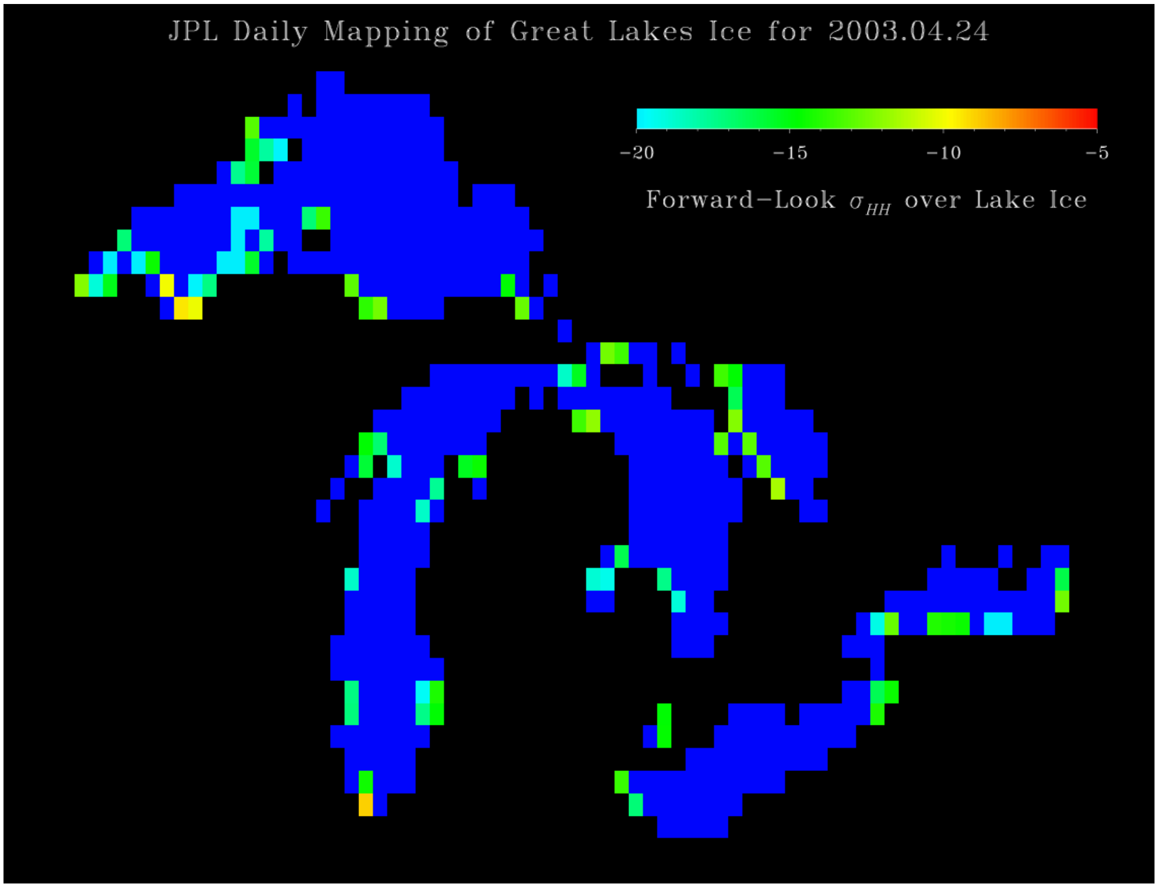
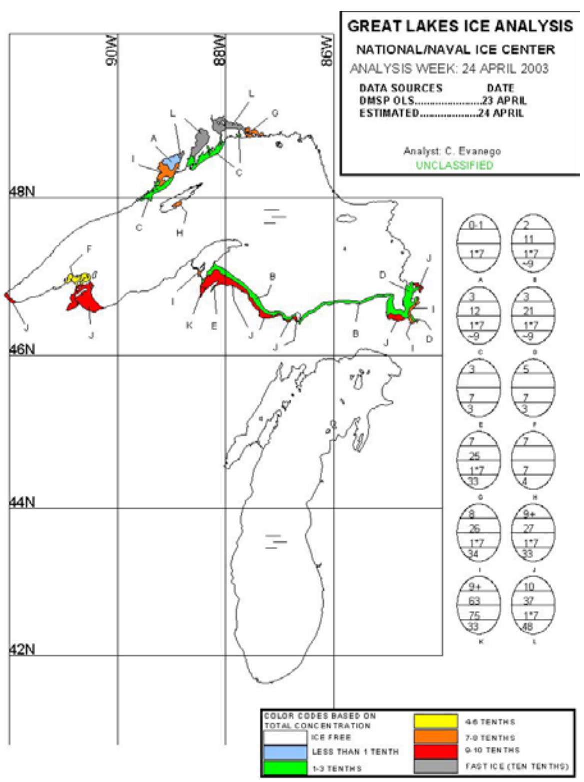


Figure 8. Ice cover over the Great Lakes observed by QSCAT (top) and NIC ice charts (bottom) for 4/10/2003.





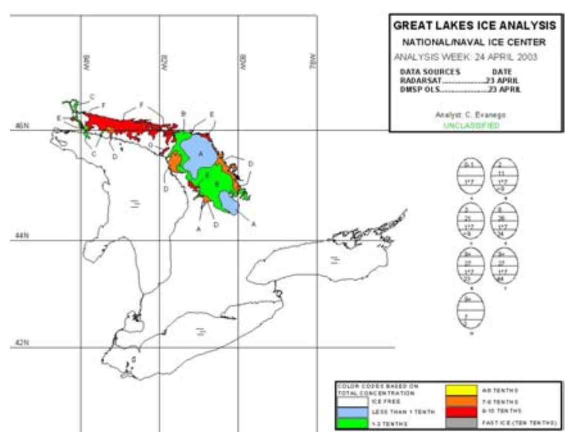


Figure 9. Ice cover over the Great Lakes observed by QSCAT (top) and NIC ice charts (bottom) for 4/24/2003.

We apply the above algorithm to map the ice cover over the Great Lakes during the last winter and spring seasons (February to April 2003). The results are presented in Figures 5-9 including QSCAT ice cover maps for 2/13/2003, 2/27/2003, 3/13/2003, 4/10/2003, and 4/24/2003 together with NIC ice charts for comparison. On 2/13/2003, Lake Erie was frozen and there were some ice-covered areas in Lake Superior, Lake Huron, and Georgian Bay (Figure 5). Two weeks later (2/27/2003), Lake Superior, Lake Erie, Lake Huron including Georgian Bay were all covered by ice as was northern Lake Michigan (Figure 6). Solid ice cover conditions were consistent in March 2003 as seen in Figure 7. In early April, the ice cover break-up process occurred and by 4/10/2003 much of the lakes were ice free except in Georgian Bay and part of Lake Superior (Figure 8). By 4/24/2003, there was no ice cover except some shore ice (Figure 9). In general, QSCAT ice mapping results and NIC ice charts agree well. However, there are differences in some cases. For example on 4/10/2003, the southern region of Lake Superior off Marquette, Michigan, was not covered by ice as seen by QSCAT while NIC ice chart still shows substantial ice cover (Figure 9). Note that data acquired by different satellite sensors on different dates were used to produce the NIC ice chart while QSCAT results were from data collected on the given date at about 6am and 6pm local time.

4.3. Web Camera at Granite Island

A web camera was installed on a lighthouse on the Granite Island in Lake Superior. It is located 5 miles off the nearest shore and about 10 miles north of Marquette, Michigan, at 46.721^{o}N and 87.411^{o}W (see Figure 10), approximately 640 ft above sea level. A photograph of Granite Island lighthouse is presented in Figure 11. For further information on the lighthouse, see http://www.uscg.mil/d9/lighthouse.html.

The web camera run on a power system consisting of propane, solar, and wind power components. There was a real-time Internet link through which images taken by the camera were transmitted to the Great Lakes Environmental Research Laboratory. The camera was controlled by software developed in Visual Basic and took images at 10 azimuth angles spanning direction from the West (270^{o}) through North to the East (90^{o}). Field observations by the web camera taken at every hour (on the half hour) of the day from early morning to late evening are to be used for verification of ice mapping by satellite data.

In Figure 12, we show a photograph taken by the Granite Island web camera at about 6:38 pm on 10 April 2003. The look direction of the camera is 30^{o} from North in the clockwise direction (close to North Northeast direction). The photograph indicates that this area on Lake Superior is largely open water with some ice cover seen on the horizon. This observation verifies QSCAT result in Figure 8, which suggests little or no ice cover over the same area. Photos in other directions at various times of the day show different ice cover conditions, which could change significantly in time and in space. Note again that the NIC ice charts in Figure 8 were derived from data on different dates (8-9 of April 2003) by RADARSAT SAR and Operational Line Scan (OLS) images. Web camera photos do show ice cover on 4/9/2003, but not as much concentration as indicated by the NIC ice chart in Figure 8 for the area near Granite Island.

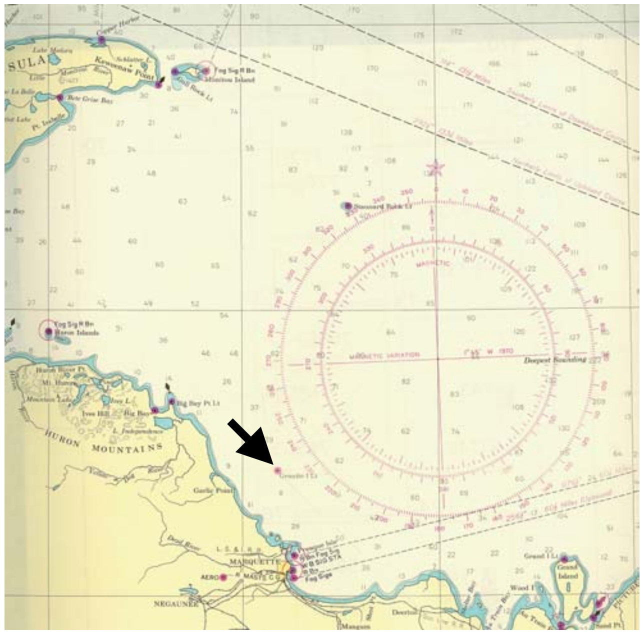


Figure 10. Location of Granite Island in Lake Superior (marked with the arrow).

Figure 11. Lighthouse on the Granite Island. The web camera was installed on the roof of the light tower.

Figure 12. Observation by our web camera from Granite Island looking over an area in Lake Superior at compass direction of 30^o (clockwise from North) close to the time of QSCAT data acquisition in the descending path on 4/10/2003.

4.4. Comparison with SAR Images

Synthetic Aperture Radar (SAR) images were acquired by the RADARSAT satellite over the Great Lakes during the 2003 ice cover season. RADARSAT SAR is operated at C band (5.3 GHz) in sun-synchronous orbits. Images acquired by RADARSAT SAR were supplied to the US National Ice Center and downloaded to GLERL for use in ice mapping research and applications over the Great Lakes. RADARSAT SAR has a swath width of about 500 km for the scan SAR wide A (SWA) mode. RADARSAT SAR images can be used to map Great Lakes ice cover with a limited coverage due to the relatively narrow swath. However, there can be misclassification of ice types owing to different wind speeds/directions because RADARSAT SAR has only horizontal-polarization backscatter data. The advantage of RADARSAT SAR images is the high spatial resolution. We compare RADARSAT images collected over Lake Superior with QSCAT results in Figure 13. The top image is ice cover observed by QSCAT on 18 March 2003 (NIC ice charts were produced only once a week and were not made for 3/18/2003). Lake Superior was almost completely ice covered on 3/18/2003 as verified by the RADARSAT SAR images in the bottom two panels of Figure 13, (both western and eastern sides of Lake Superior). Note that the RADARSAT SAR images in Figure 13 do not cover the northern portion of Lake Superior. We also have a concurrent ENVISAT SAR image (see Figure 14) covering the northern area of the lake.

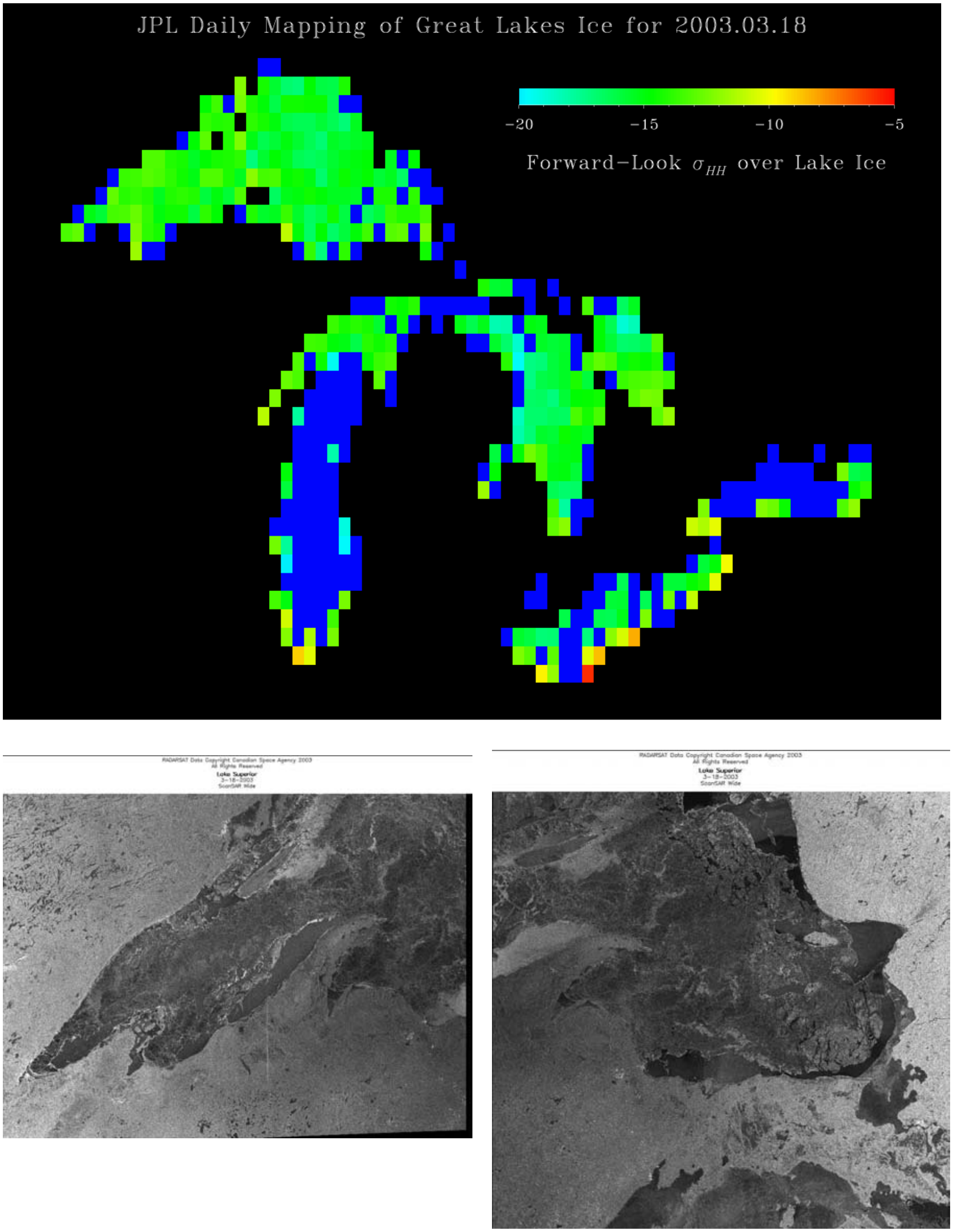


Figure 13. Comparison of QSCAT ice cover image and RADARSAT SAR backscatter (horizontal polarization) images on 3/18/2003 (NIC ice chart was not made for this date).

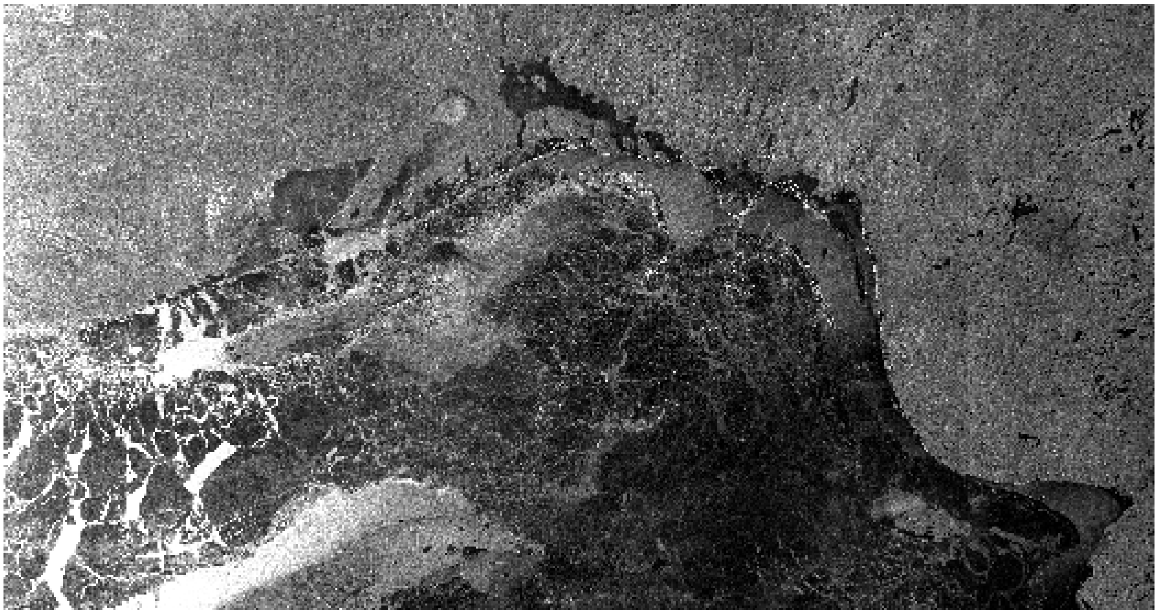


Figure 14. ENVISAT ASAR Wide-Swath backscatter image acquired with vertical polarization over Lake Superior on 18 March 2003. This image covers the northern portion of Lake Superior, which is complementary to the RADARSAT SAR images in Figure 13, covering other regions of the lake. The ASAR image reveals ice cover in Lake Superior within the ENVISAT swath verifying QSCAT ice mapping results in Figure 13.

4.5. GLAWEX 2003

While satellite images from other sensors, and/or products derived from satellite data can be used to verify ice mapping results obtained from QSCAT data, actual surface truth from direct field experiments are necessary to validate satellite results. For this purpose, we carried out field experiments using the U.S. Coast Guard Icebreaker USCGC Mackinaw in 2003 and 2002. During this past winter (March 2003), field observations and ground truth were collected along the ship track of the Mackinaw across Lake Superior. The Mackinaw locked through at Sault Ste. Marie on 16 March 2003, cut across the lake, and arrived at Duluth on 20 March 2003, then returned back across Lake Superior arriving at Sault Ste. Marie on 26 March 2003. In Figure 15, we show two different ice types: brash ice and pancake ice in Lake Superior. Under freezing conditions, brash ice, typically observed in Whitefish Bay, has strong backscattering effects owing to roughness and the complex volumetric matrix of deformed ice pieces. In Figures 6 (2/27/2003) and 7 (3/13/2003), QSCAT backscatter over the Whitefish Bay is strong owing to areas of brash ice. However, the backscatter became notably lower by 3/18/2003 over areas of brash ice. This is because the ice had been deteriorating and became candled over various areas, with wet snow cover. During that time, field measurements indicate that air temperatures were well above freezing during much of the day. These results suggest that, at Ku band, we need to detect the melting condition and to classify ice types only when the ice is under frozen conditions.

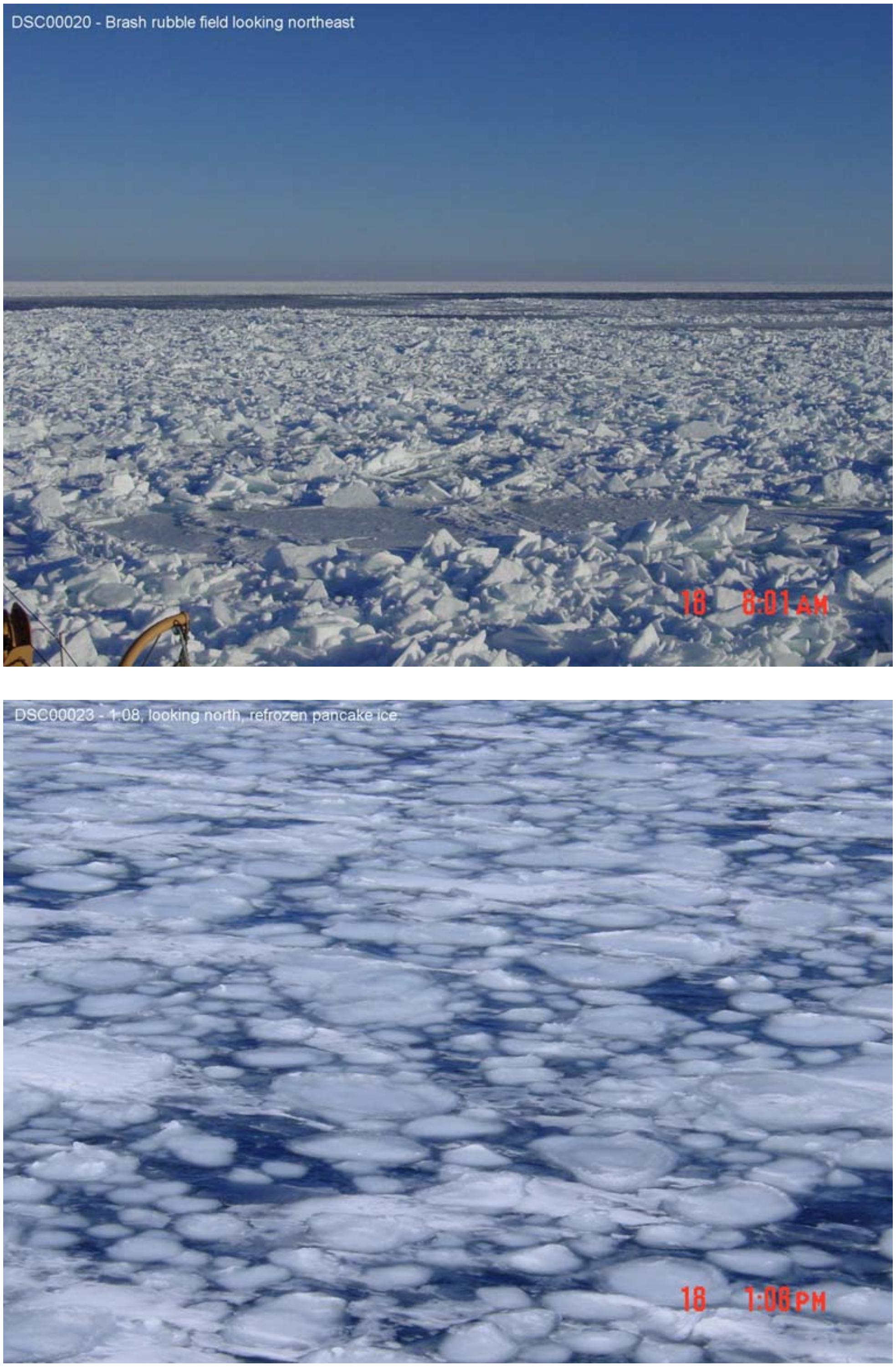


Figure 15. Field observations during GLAWEX 2003 for brash ice just pass White Fish Point and pancake ice about 20 miles NW of White Fish Point on 3/18/2003.

4.6. GLAWEX 2002

The Great LAkes Winter EXperiment (GLAWEX 2002) was carried out in February-March 2002 using the NASA/JPL AIRSAR system aboard the NASA DC-8 aircraft deployed along the USCGC Mackinaw icebreaker ship tracks over various locations in Lake Superior, Lake Huron, and Lake Michigan. GLAWEX 2002 was conducted by the NOAA Great Lakes Environmental Research Laboratory (GLERL) and the Jet Propulsion Laboratory (JPL), with ship and helicopter support from the United States Coast Guard (USCG).

In GLAWEX 2002, the NASA DC-8 aircraft (Figure 16) carrying the NASA/JPL AIRSAR system was deployed to the Great Lakes, making multiple flights from Madison, Wisconsin. AIRSAR collected polarimetric and interferometric SAR data over various ice types. The SAR frequencies include P, L, and C bands. AIRSAR data have multiple polarimetric and interferometric modes. Under NASA support, AIRSAR was deployed in three phases during February and March 2002 to acquire data along USCGC Mackinaw icebreaker ship tracks. Figure 17 presents the AIRSAR data collection map in Lake Superior, Lake Huron, Lake Michigan, and St. Mary River.

Figure 16. NASA DC-8 aircraft carrying AIRSAR system deployed for GLAWEX 2002.

We coordinated the Great Lakes field campaign for concurrent USCG ship and NASA aircraft deployment. Field observations and in-situ measurements were obtained from the USCGC Mackinaw. Ice thickness, ice and snow characteristics, and environmental data were collected at many locations where the USCGC Mackinaw stopped for field observations. Lake ice cores were also taken to measure ice density and ice layer structure. Air reconnaissance flights were carried out by USCG helicopter for ice observations during GLAWEX 2002.

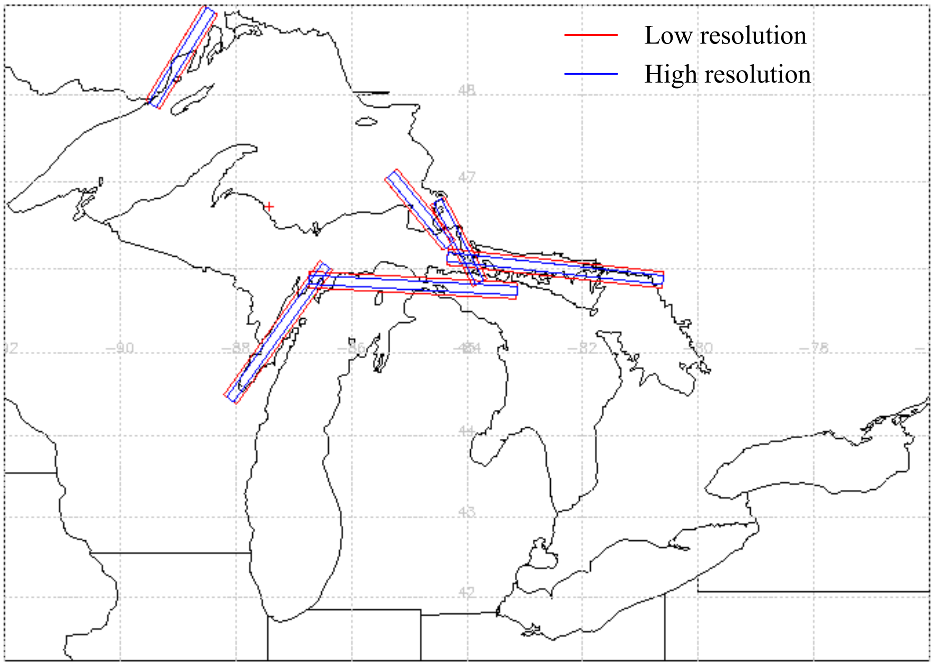


Figure 17. AIRSAR data collection map showing low and high resolution areas of coverage over the Great Lakes.

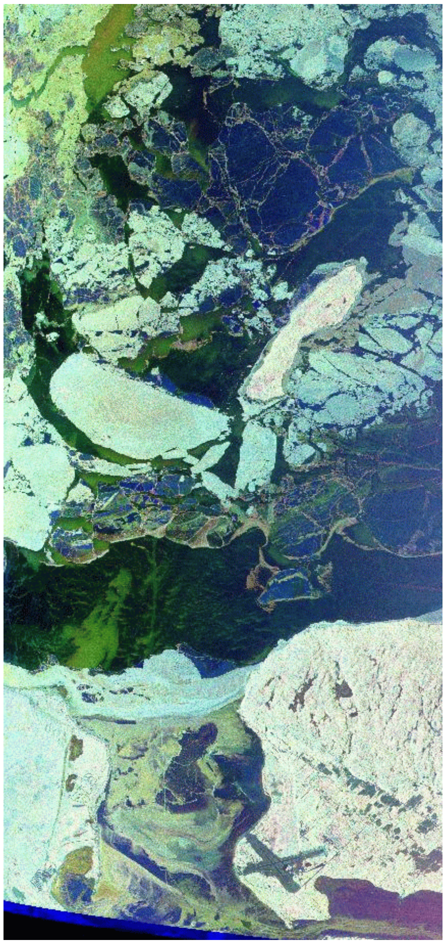


Figure 18. (a) Left panel is an AIRSAR false-color image of a portion of Whitefish Bay containing various ice types, and (b) Right panel is an aerial photo of the Sault Ste. Marie airport (from the web site http://www.saultairport.com/physicallayout.html) that appears as the X-shaped feature near the bottom of the SAR image.

The left panel of Figure 18 shows an AIRSAR (POLSAR) image of a portion of Whitefish Bay on Lake Superior (March 20, 2002). The X-shaped feature near the bottom of the SAR image is the Sault Ste. Marie Airport, whose aerial photo is in the right of Figure 18 (Sault Ste. Marie Airport Development Corp.). The SAR synthesized false color image composed of bands C (HH, blue), L (VV, green), and P (VV, red) reveals different ice types in the ice cover. The color indicates the roughness/ice volume of the different ice types at each respective band. White indicates sufficient roughness/ice volume at all bands. For example, the white colored band of brash ice spanning the lower portion of the bay (northwest of the airport) is at least 4.5 ft. thick. Further details of GLAWEX 2002 can be found in a report by Nghiem and Leshkevich [*Great LAkes Winter EXperiment 2002 - SAR Applications to Ice-Covered Lakes and Rivers, Tech. Rep.*, 2003]. Although there was little ice cover in February-March for a direct comparison with QSCAT results, GLAWEX 2002 data are applicable for current and future ice mapping with SAR data to be used in turn to verify QSCAT ice mapping.

5. Great Lakes Ice Cover Prototype Product Derived from QSCAT Data

Ice cover extent is mapped with QSCAT data and ice backscatter is gridded with a resolution of 1/12^{o} in latitude and longitude in the prototype product (Figure 19).

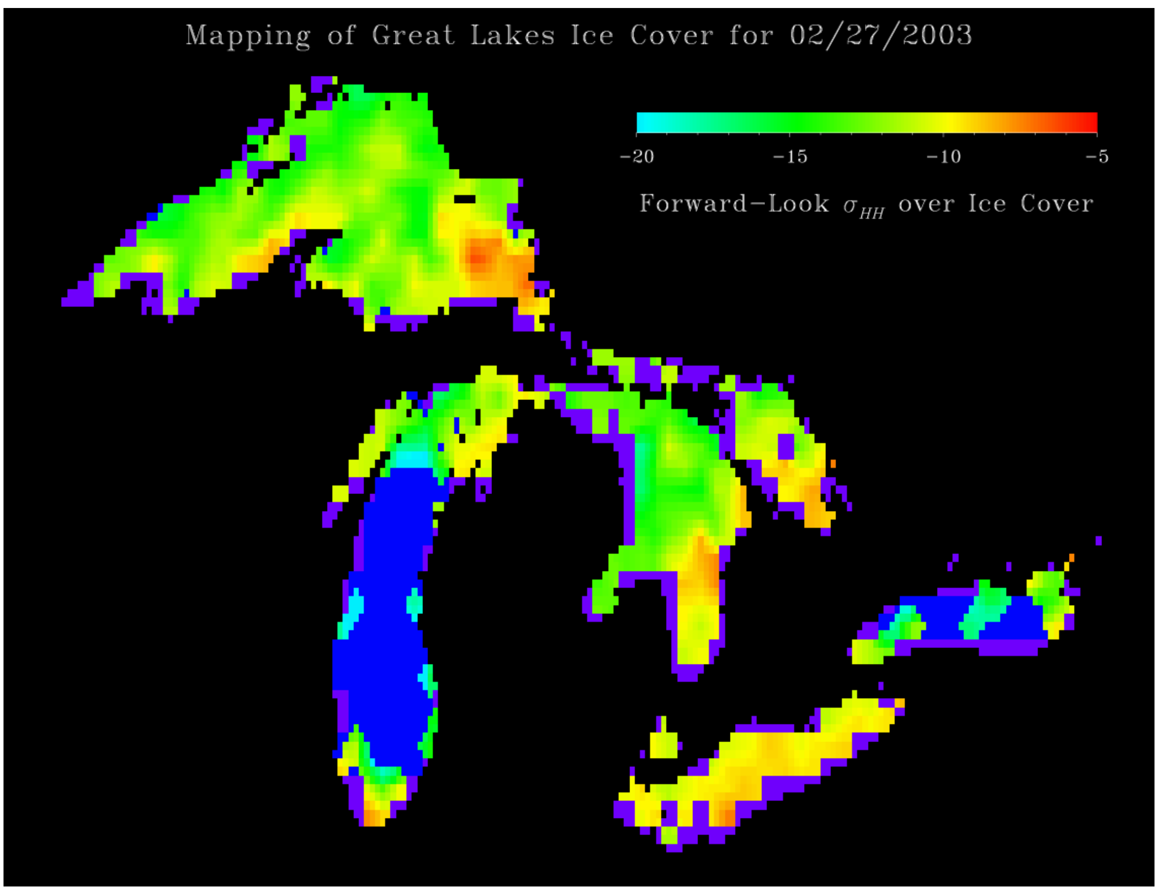
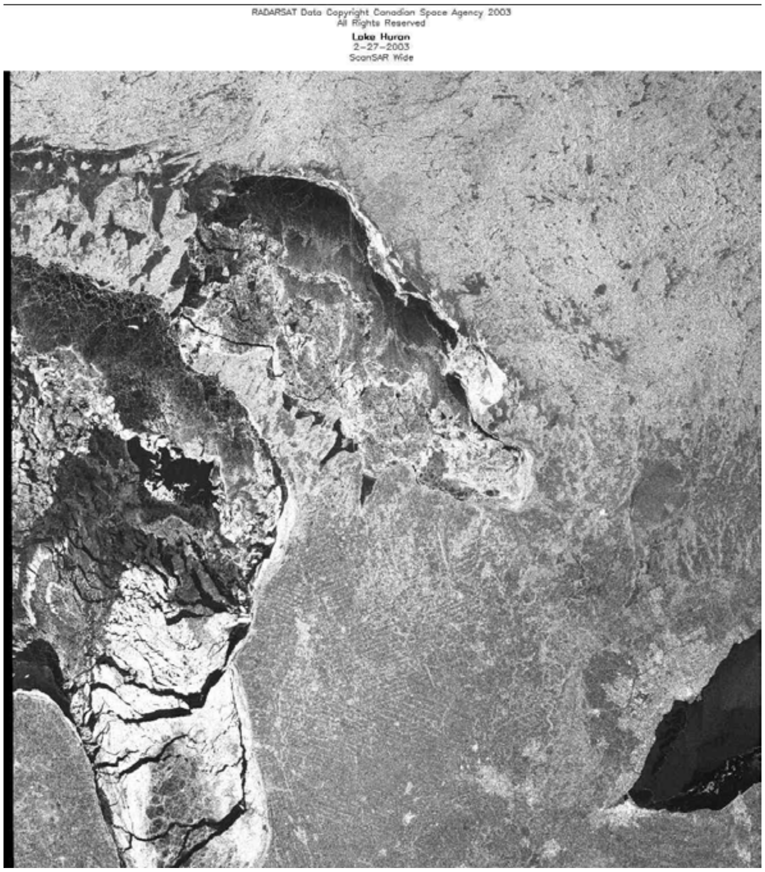


Figure 19. Prototype of ice-cover product for the Great Lakes: green-red for ice, blue for water, and violet for unclassified areas.



We compare QSCAT result in Figure 19 with the RADARSAT SAR backscatter image in Figure 20. The SAR image shows ice cover over most of Lake Huron portion and the Georgian Bay seen within the SAR swath. This agrees and thus verifies QSCAT result in Figure 19. Furthermore, the high-backscatter area in the south of Lake Huron (orange-red area in the QSCAT image) corresponds to the bright area in the SAR image in Figure 20.

Figure 20. RADARSAT SAR backscatter image in scan SAR wide A mode over Lake Huron and the Georgian Bay on 2/27/2003.

On 26 February, the MODIS multi-spectral sensor on the NASA Terra Satellite acquired an image over Lake Superior, northern Lake Michigan, and western Lake Huron fortuitously under a relative clear sky condition as shown in Figure 21. The ice cover over the lakes seen by MODIS is consistent with the QSCAT result observed a day later (Figure 19).

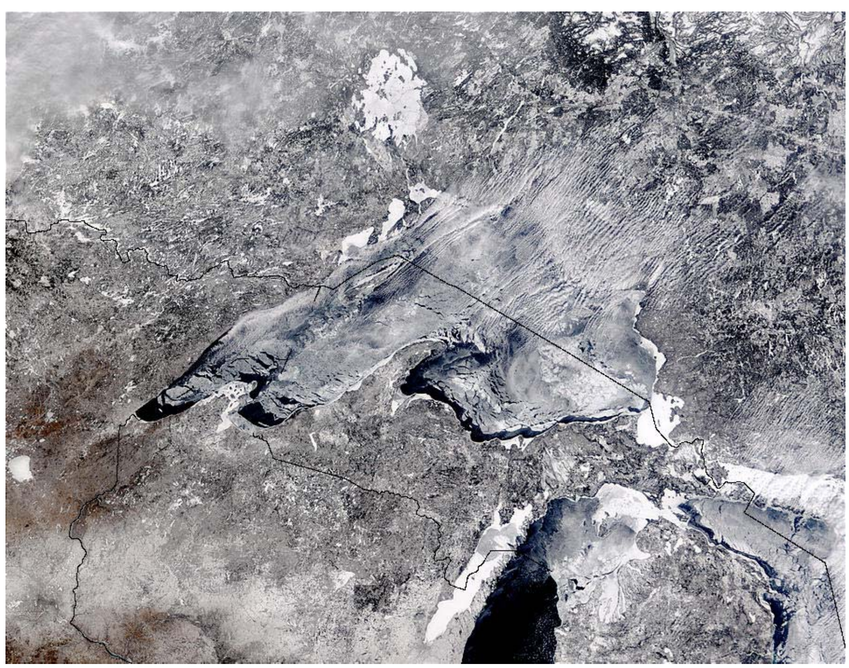


Figure 21. MODIS image on 2/26/2003.

6. FUTURE EXTENSION FOR GREAT LAKES ICE MAPPING WITH SCATTEROMETER DATA

We have successfully used QSCAT satellite scatterometer data to map ice cover over the Great Lakes on a daily basis. However, the algorithm can be improved, composite ice products can be developed, and long-term results using present QSCAT data and new Midori-II/SeaWinds data can be obtained. We suggest the following future extensions:

- Developing more complex algorithms with combinations of higher resolution scatterometer data such as slice data to obtain ice mapping with better spatial resolution
- Deriving surface melt conditions over Great Lakes ice cover (melting and freezing conditions) and classifying ice types under freezing conditions
- Using ice masks to determine open water areas and obtaining wind speed and wind direction over water surface areas; an example of wind field derived for open water over the Great Lakes is presented in Figure 22
- Developing advanced composite products that include information on ice cover area, ice types, surface melt conditions, and wind speed and direction
- Obtaining long-term results over the Great Lakes from present and future satellite scatterometer data sets in combination with other satellite data, with Great Lakes Marine environmental data, and with Great Lake geophysical models.
- For future satellite scatterometers, a resolution of 1 to 5 km, a swath of 2000 km and a dual co-polarization capability are necessary to accurately map ice cover over the entire Great Lakes on a daily basis.

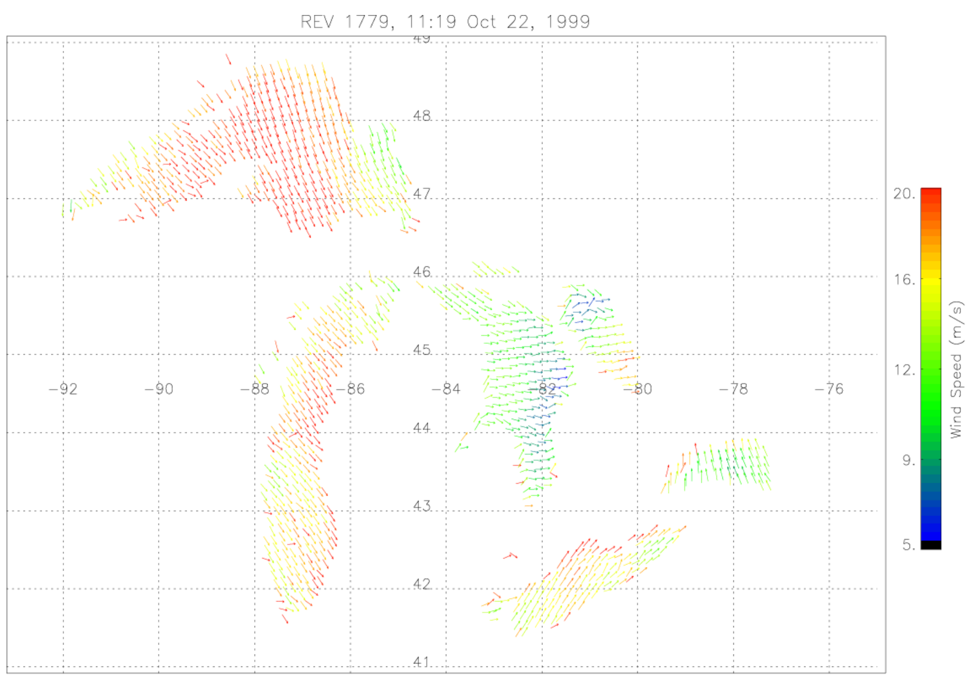


Figure 22. Example of wind speed and direction derive from QSCAT over open water during a storm over the Great Lakes in October 1999. Such product can be combined with ice products to develop a wind-ice composite product during the ice season.

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